

Linear Radii and Effective Temperatures of Carbon Stars

Gerard T. van Belle

Jet Propulsion Lab

Robert R. Thompson

Jet Propulsion Lab/University of Wyoming

195th Meeting of the American Astronomical Society

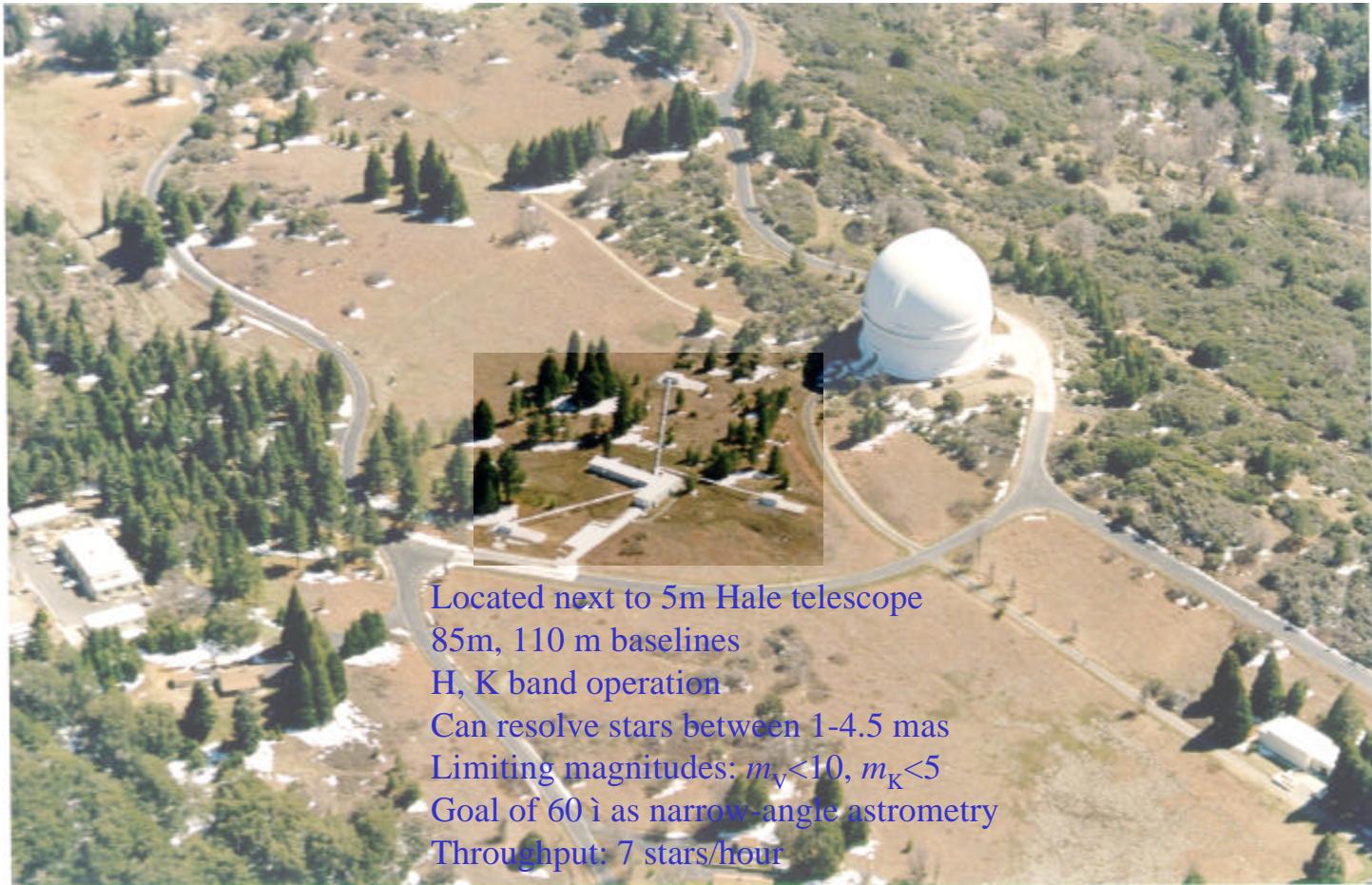
Atlanta, GA

January 13, 2000

Abstract

We report new interferometric angular diameter observations of 32 carbon stars as measured with the Palomar Testbed Interferometer (PTI). Combining these with previously published diameters for 22 other carbon stars, primarily found in the Infrared-Optical Telescope Array (IOTA) investigation of Dyck, van Belle & Benson (1996), we are able to compute effective temperatures and linear radii for 52 stars. Consistent with the previous IOTA investigation of these objects, the average temperature of entire sample is roughly 2700K; we also demonstrate effective temperatures appear to increase towards “later” spectral types. Using the distance estimates to these objects as found in Claussen *et al.* (1987) the mean radius for the entire carbon star sample is estimated to be $350 \pm 70 R_{\odot}$. As such, these stars appear quite similar in effective temperature and radius to oxygen-rich Mira variables (van Belle *et al.* 1997). We note that the linear size of our observed sample as indicated by Hipparcos parallaxes appears to be systematically smaller by a factor of two. We expect this to be an artifact of the satellite observations and stellar surface morphology rather than a phenomenon intrinsic to the spatial distribution of the observed carbon stars.

Palomar Testbed Interferometer



Located next to 5m Hale telescope
85m, 110 m baselines
H, K band operation
Can resolve stars between 1-4.5 mas
Limiting magnitudes: $m_V < 10$, $m_K < 5$
Goal of 60 mas narrow-angle astrometry
Throughput: 7 stars/hour

The Data

- 58 observations of 52 carbon and S-type stars
- Angular sizes from the Palomar Testbed Interferometer
 - 30 carbon stars observed with PTI
- Additional sources
 - 15 stars observed with IOTA, Dyck *et al.* 1996
 - 7 stars from previous papers: Lasker et al. 1973, de Vegt 1974, Dunham *et al.* 1975, Ridgway *et al.* 1982, Quirrenbach *et al.* 1994

The Data. II

- Two stars (AQ And, Z Psc) observed by PTI and IOTA
 - Sizes in agreement
- Two stars (NZ Gem, V2141 Cyg) unresolved by IOTA but resolved by PTI
 - Consistent with spatial resolution of PTI (1.5-4.5 mas) and IOTA (4.5-20 mas)

| Name | HD | Spectral type (1) | Spectral type (2) | theta | thetaerr | Fbol | T (K) | Terr | R (Rsun) | Reference |
|-----------|--------|----------------------|-------------------|-------|----------|-------|-------|------|----------|------------|
| AD Cyg | 195665 | S5,8V | | 2.65 | 0.13 | 26.6 | 3228 | 137 | | PTI |
| AQ And | 2342 | C5,4 | C-N5+ | 4.09 | 0.82 | 33.6 | 2787 | 280 | 383 | IOTA |
| AQ And | 2342 | C5,4 | C-N5+ | 3.63 | 0.08 | 33.6 | 2928 | 48 | 339 | PTI |
| AQ Sgr | 184283 | C7,4 | C-N5 | 6.13 | 0.52 | 67.0 | 2704 | 116 | 370 | Lunar occ. |
| BL Ori | 44984 | C6,3 | | 3.64 | 0.08 | 85.3 | 3686 | 47 | 224 | PTI |
| BM Gem | 57160 | C5,4J | | 2.21 | 0.04 | 13.5 | 2986 | 407 | 358 | PTI |
| CIT 13 | | C? | | 11.04 | 0.41 | 58.5 | 1949 | 109 | 1224 | IOTA |
| CR Gem | | C8,3 | | 3.87 | 0.09 | 35.7 | 2878 | 48 | 325 | PTI |
| CR Psc | 6409 | S star? | | 2.00 | 0.06 | 13.5 | 3139 | 117 | | PTI |
| DR Ser | | C5,4 | | 4.20 | 0.14 | 22.4 | 2456 | 54 | 448 | PTI |
| HDC178690 | 178690 | ? | | 2.22 | 0.04 | 21.0 | 3324 | 79 | | PTI |
| HK Lyr | 173291 | C7,4 | | 3.60 | 0.06 | 31.5 | 2891 | 33 | 349 | PTI |
| HR Peg | 216672 | S5,1 | | 3.88 | 0.04 | 84.0 | 3557 | 33 | | PTI |
| LW Cyg | 208512 | C5,4 | | 4.09 | 0.07 | 28.1 | 2637 | 28 | 379 | PTI |
| NO Aur | 37536 | M2III ^s ? | | 3.84 | 0.07 | 79.0 | 3521 | 49 | | PTI |
| NZ Gem | 61913 | M3svar | | 3.71 | 0.18 | 104.6 | 3846 | 124 | | PTI |
| R Gem | 53791 | S3,9e | | 2.89 | 0.05 | 16.5 | 2746 | 62 | | PTI |
| RS Cyg | 192443 | C8,2 | C-N5.5 | 4.39 | 0.82 | 61.1 | 3124 | 293 | 317 | IOTA |
| RT Cap | 192737 | C6,4 | | 8.18 | 0.21 | 79.4 | 2444 | 34 | 458 | Lunar occ. |
| RT Ori | 36602 | C6,4 | C-N5 | 4.50 | 0.92 | 28.0 | 2538 | 262 | 460 | IOTA |
| RV Aur | 46321 | C4,5 | | 2.01 | 0.08 | 8.9 | 2823 | 54 | 333 | PTI |
| RV Cyg | 206750 | C6,4 | C-N5: | 7.77 | 0.51 | 100.9 | 2662 | 91 | 401 | IOTA |
| RV Mon | 51620 | C4,4 | | 3.42 | 0.07 | 44.8 | 3241 | 57 | 368 | PTI |
| RX Peg | 208526 | C4,4J | | 2.95 | 0.14 | 17.2 | 2745 | 76 | 372 | PTI |
| RZ Peg | 209890 | C9,1e | | 3.11 | 0.02 | 14.1 | 2544 | 64 | 492 | PTI |
| S Aur | | N0V? | | 9.10 | 0.61 | 27.9 | 1783 | 73 | 970 | IOTA |
| SU And | 225217 | C6,4 | | 2.37 | 0.14 | 15.9 | 3001 | 97 | 291 | PTI |
| SY Per | | C6,4 | | 3.47 | 0.82 | 20.9 | 2688 | 322 | 355 | IOTA |

The Data. III

- Spectral type references
 - 1 – Yamashita
1972, 1975,
SIMBAD
 - 2 – Barnbaum *et al.*
1996

| Name | HD | Spectral type (1) | Spectral type (2) | theta | thetaerr | Fbol | T (K) | Terr | R (Rsun) | Reference |
|-----------|--------|-------------------|-------------------|-------|----------|-------|-------|------|----------|------------|
| SZ Sgr | 161208 | C7,3 | C-N5.5 | 3.37 | 0.21 | 20.7 | 2720 | 88 | 367 | Lunar occ. |
| TT Cyg | 186047 | C5,4 | | 3.30 | 0.07 | 25.4 | 2861 | 37 | 344 | PTI |
| TU Tau | 38218 | C5,4 | | 3.90 | 0.08 | 30.3 | 2751 | 40 | 542 | PTI |
| TW Oph | 158377 | C5,5 | C-N5 | 10.63 | 0.52 | 100.1 | 2271 | 57 | 526 | Lunar occ. |
| TX Psc | 223075 | C7,2 | C-N5 | 9.50 | 0.83 | 289.7 | 3133 | 137 | 286 | Lunar occ. |
| TX Psc | 223075 | C7,2 | C-N5 | 11.44 | 0.31 | 289.7 | 2855 | 41 | 345 | IOTA |
| TX Psc | 223075 | C7,2 | C-N5 | 11.45 | 1.04 | 289.7 | 2855 | 131 | 345 | Mark III |
| U Lyr | | Ne... | | 3.66 | 0.09 | 18.0 | 2495 | 60 | 441 | PTI |
| UU Aur | 46687 | C6,4 | C-N5- | 12.37 | 0.22 | 317.1 | 2809 | 31 | 399 | Mark III |
| V Aql | 177336 | C5,4 | C-N5 | 10.32 | 0.72 | 138.1 | 2498 | 89 | 422 | IOTA |
| V Cyg | | C7,4e? | | 4.10 | 0.13 | 121.1 | 3794 | 87 | 256 | PTI |
| V2141 Cyg | 199799 | S star? | | 3.15 | 0.40 | 45.2 | 3385 | 218 | | PTI |
| V346 Aur | 280188 | C3II? | | 3.40 | 0.07 | 13.3 | 2396 | 183 | 297 | PTI |
| V460 Cyg | 206570 | C6,3 | C-N5 | 6.44 | 0.61 | 111.3 | 2996 | 147 | 333 | IOTA |
| V530 Lyr | 170970 | S star? | | 1.79 | 0.03 | 18.5 | 3583 | 105 | | PTI |
| V613 Mon | 49368 | S5,1 | | 1.75 | 0.16 | 22.6 | 3813 | 201 | | PTI |
| VW Gem | 47883 | C5,4 | | 2.18 | 0.04 | 11.6 | 2893 | 144 | 315 | PTI |
| VX And | 1546 | C4,5 | C-J4.5 | 6.75 | 0.61 | 56.8 | 2473 | 115 | 450 | IOTA |
| VX Gem | 55284 | C7,2e | | 2.12 | 0.10 | 8.3 | 2697 | 63 | 358 | PTI |
| VY And | | C3,4? | | 2.45 | 0.02 | 8.1 | 2491 | 22 | 370 | PTI |
| W Ori | 32736 | C5,4 | C-N5 | 9.91 | 0.61 | 243.0 | 2936 | 98 | 373 | IOTA |
| WZ Cas | 224855 | C9,2 | | 5.93 | 0.72 | 87.0 | 2936 | 179 | 306 | IOTA |
| X Cnc | 76221 | C5,4 | C-N4.5 | 8.38 | 0.62 | 128.3 | 2722 | 103 | 406 | Lunar occ. |
| Y CVn | 110914 | C5,5 | C-J4.5 | 11.86 | 0.31 | 320.5 | 2876 | 48 | 370 | IOTA |
| Y CVn | 110914 | C5,5 | C-J4.5 | 15.13 | 0.53 | 299.7 | 2505 | 47 | 472 | Mark III |
| Y Tau | 38307 | C6,4 | C-N5- | 8.58 | 0.01 | 126.2 | 2678 | 22 | 453 | Lunar occ. |
| YY Cyg | | N0V? | | 2.33 | 0.65 | 9.7 | 2681 | 378 | 325 | PTI |
| Z Psc | 7561 | C7,2 | C-N5 | 4.38 | 0.21 | 57.8 | 3051 | 114 | 283 | PTI |
| Z Psc | 7561 | C7,2 | C-N5 | 4.91 | 0.72 | 57.8 | 2913 | 228 | 317 | IOTA |

Basic Parameters

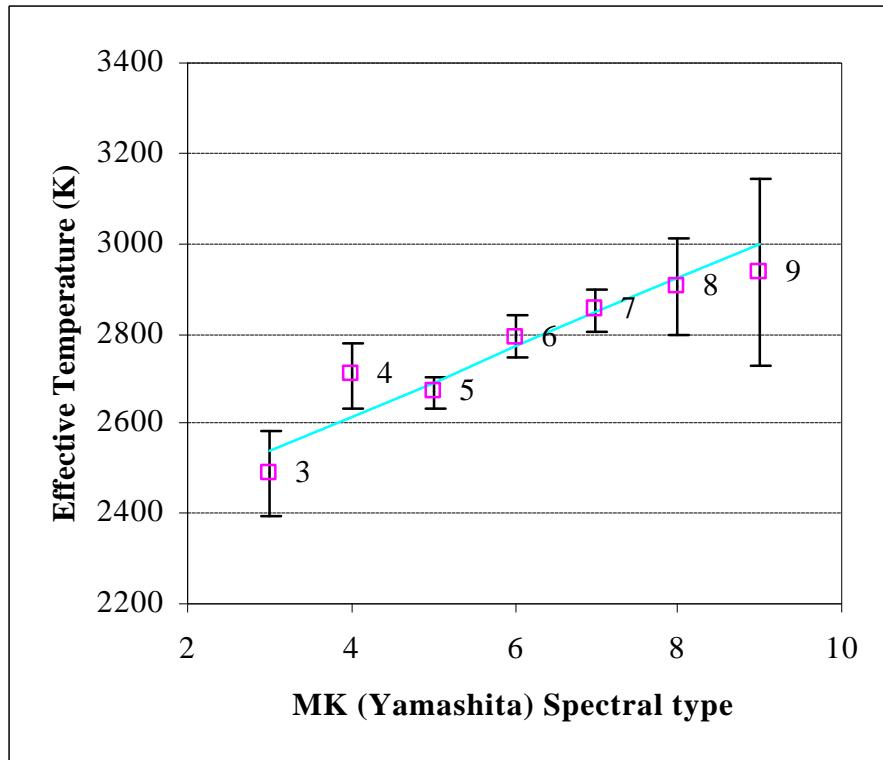
- *Effective temperature* is defined as: $L = 4\pi s R^2 T_{\text{EFF}}^4$,
which can be rewritten as: $T_{\text{EFF}} = 1.316 \times 10^7 \left(\frac{F_{\text{TOT}}}{q_R^2} \right)^{1/4}$
 - F_{TOT} is the bolometric flux (W cm^{-2}), q_R is the Rosseland mean stellar angular diameter (mas)
- *Linear radius* is simply: $R = \frac{1}{2} q \times d$
 - Hipparcos (Perryman *et al.* 1997) distances now available but problematic for carbon stars (see below)
 - Distances from $M_K = -8.1$ estimates of Claussen *et al.* (1987)

Variability

- No statistically significant variations in angular size over time
- No statistically significant variations in angular size with projected baseline

Temperature

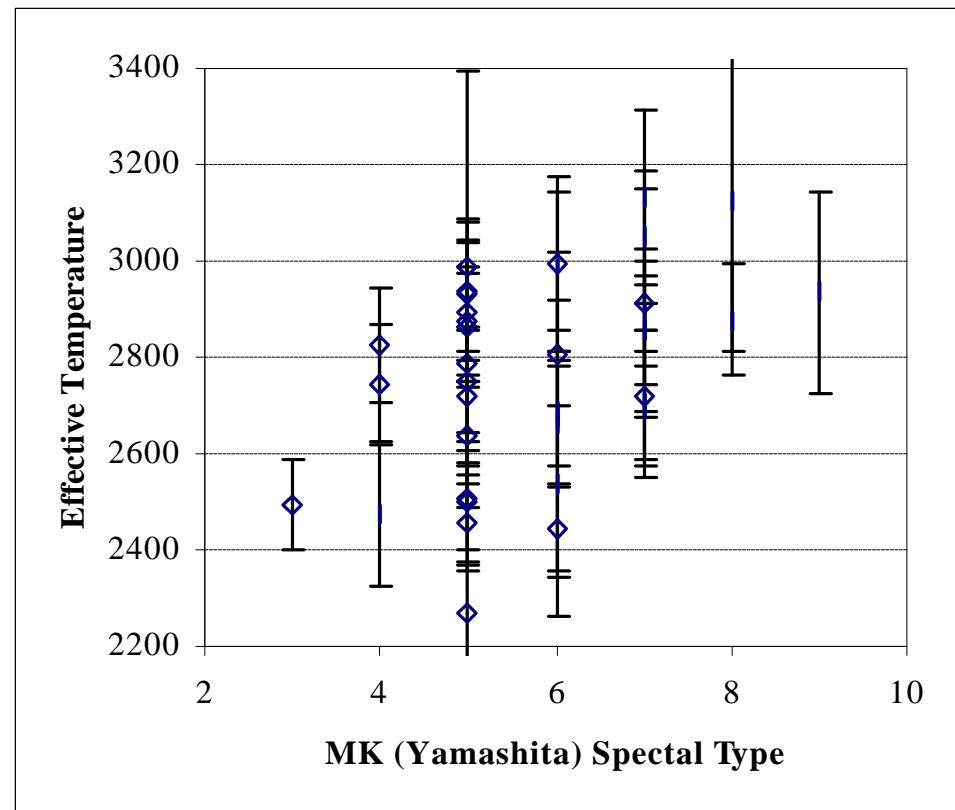
- As a function of MK spectral class as determined by Yamashita (1972, 1975)
- Temperature increase towards “later” spectral types
 - First noted by Tsuji (1981a,b) and indicated previously (Dyck *et al.* 1996)
 - $T = 76 \times C + 2310$ K
- Consistent with presence of M-S bands as indicated by Dominy (1985) (linked to SiC_2)



| Class | N | T (K) | δ_T | Std. Dev. |
|-------|----|-------|------------|-----------|
| C3 | 1 | 2491 | 94 | |
| C4 | 3 | 2706 | 73 | 183 |
| C5 | 14 | 2669 | 33 | 217 |
| C6 | 9 | 2794 | 45 | 370 |
| C7 | 9 | 2850 | 46 | 152 |
| C8 | 2 | 2906 | 106 | 174 |
| C9 | 1 | 2936 | 209 | |

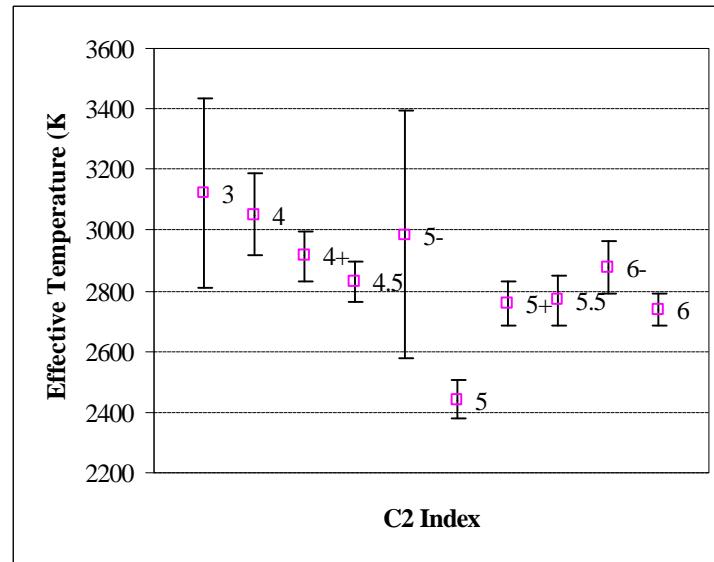
Temperature Dispersion

- Fit $\Delta T_{\text{rms}} = 231 \text{ K}$ for 39 stars; average of 5.6 stars per subtype $\rightarrow 98 \text{ K}$ uncertainty per subtype
- Natural spread
 - Individual T errors: $\Delta T_{\text{rms}} = 170 \text{ K}$
 - Potential spectral misclassification: $\Delta T = 75 \text{ K}$
 - Remaining dispersion: $\Delta T = 140 \text{ K}$



Temperature: Revised MK System

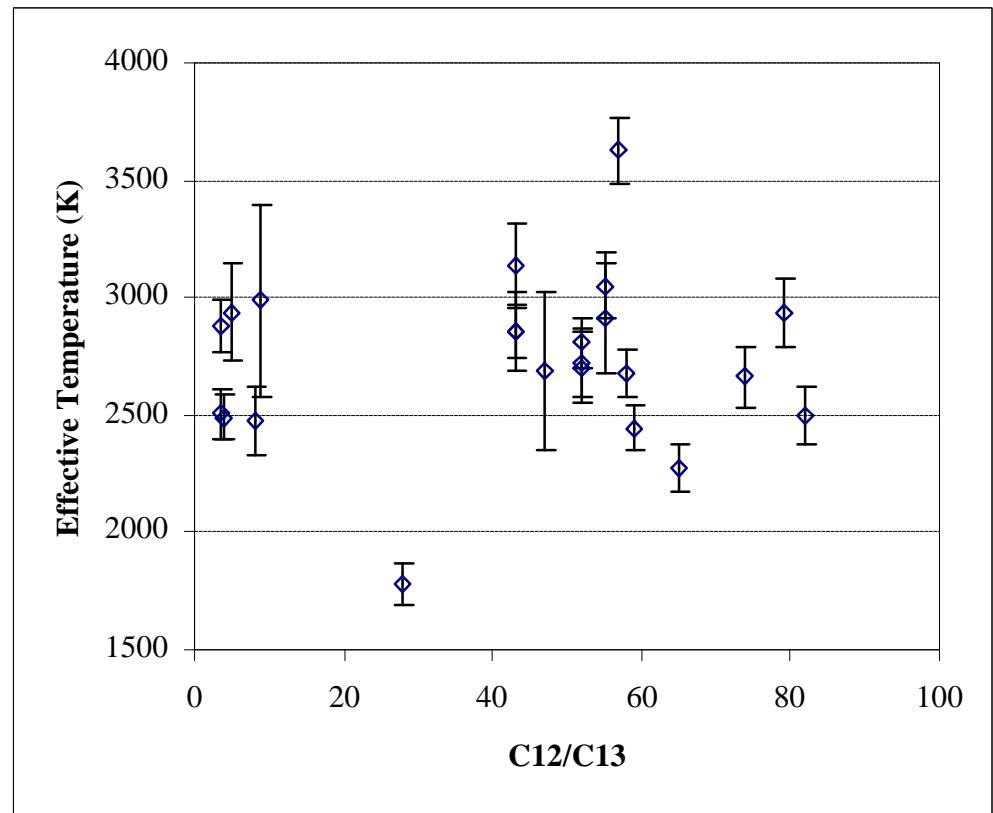
- Revised MK spectral type, C₂ indices published in Barnbaum *et al.* (1996)
- Average temperature by subtype
 - C-J (N=5): 2660 ± 60 K
 - C-N (N=24): 2810 ± 30 K
 - $\Delta T_{rms} = 250$ K
- Potential dependency of T with increasing C₂ index



| C ₂ | | | | |
|----------------|---|-------|------------|--|
| Index | N | T (K) | σ_T | |
| 3 | 1 | 3124 | 314 | |
| 4 | 1 | 3051 | 136 | |
| 4+ | 3 | 2915 | 83 | |
| 4.5 | 5 | 2830 | 64 | |
| 5- | 1 | 2986 | 407 | |
| 5 | 4 | 2440 | 64 | |
| 5+ | 3 | 2758 | 72 | |
| 5.5 | 3 | 2768 | 81 | |
| 6- | 2 | 2878 | 87 | |
| 6 | 4 | 2738 | 54 | |

$^{12}\text{C}/^{13}\text{C}$ Ratios

- Using previously published $^{12}\text{C}/^{13}\text{C}$ ratios (Lambert et al. 1996, Abia & Isern 1996), can look for correlations with temperature
- None apparent – indicates depletion of ^{13}C does not affect effective temperature
- Significance of S Aur's low T in gap of $10 < ^{12}\text{C}/^{13}\text{C} < 40$?



Linear Radius

- Average size of 350 ± 70 R_{\odot}
- Apparent radius increase towards “later” spectral types is not statistically significant
- Sizes and temperatures consistent with those of oxygen-rich Miras (van Belle *et al.* 1997)

